Forecasting Applications of High Resolution Diurnal Satellite Cloud Composite Climatologies over Former Yugoslavia and the Adriatic Sea

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1. Introduction

Clouds are a primary obstacle for military systems requiring visual or infrared target acquisition. In the past fifteen years, satellite data has greatly advanced our understanding of clouds. In this study we expand on an idea put forward by Reinke et al. (1992). They suggested that high resolution satellite cloud climatologies could be used to create a forecasting tool through a combination of cloud frequency of occurrence and cloud persistence composites.

In this paper we describe forecasting tools developed using the new Climatological and Historical ANalysis of Clouds for Environmental Simulations (CHANCES) database (Vender Haar et al. 1995). The results show the utility of similar satellite derived climatologies for various modeling and operational forecasting applications. The analysis is limited to the summer season for a domain centered over the former Yugoslavia and Adriatic Sea. Specific target forecast applications are demonstrated for satellite data centered over the city of Sarajevo.

2. Background

Kornfield et al. (1967) created the first cloud composites for research by sequentially superimposing satellite images on photographic paper. The early composites were useful for the study of large-scale cloud systems and the general circulation. Eighteen years later Klitch et al. (1985) ushered the compositing technique into the computer age by constructing cloud composites entirely in the digital domain. They used satellite composites to study the relation of convection to terrain in Colorado. More recently, Gibson and Vender Haar (1990) completed a similar study of convection in the southeastern United States.

On a global scale, there are two primary ongoing satellite cloud climatology projects. The International Satellite Cloud Climatology Project (ISCCP) has created a global database of many cloud properties using visible and infrared satellite data with 3hr temporal, and 250x 250 km spatial resolution. Statistics for some regional data are also available at resolutions as low as 30km (Rossow 1993). The U.S. Air Force produces a cloud composite for operational purposes called the real-time nephanalysis (RTNEPH) (Kiess and Cox 1988). The RTNEPH is a combination of satellite and surface data and has 47 km horizontal resolution. Cloud climatologies have been created using RTNEPH (Hughes and Henderson-Sellers 1985), however, clouds vary significantly on much finer scales.

A very fine space/time domain is crucial to understanding clouds in relation to mesoscale forcings (Reinke et al. 1992), and hence is critical to the creation of cloud climatology composites that can be used as forecast tools. This is specifically true for Terminal Aerodrome Forecasts (TAFS) and remote location target forecasts for offensive operations, reconnaissance and as inputs to electro-optical tactical/meteorological decision aids. Vender Haar et al. (1993) show that the RTNEPH cloud database as well as Probability-of-Cloud-Free-Line-of-Sight

(PCFLOS) models can be significantly improved through the development and use of a high resolution satellite cloud database.

Today's PCFLOS models are based on surface observations derived on a spatial resolution of approximately 200 km. The results presented by Vender Haar et al. (1993) show that approximately 90 percent of all cloud-free intervals are less than 10km. So, climatological forecasts and models based on surface data will not provide a representative measure of the impact of clouds in many geographic locations (Reinke et al. 1995).

The CHANCES database used in this study was sponsored by a Small Business Innovative Research (SBIR) Phase II, U.S. Air Force grant. The purpose was to produce a 1-yr, 1-hr, 5-km resolution global cloud/no cloud (CNC) database product and to demonstrate the feasibility of producing a longer term (5-yr) climatological cloud database. CHANCES is ideal for the construction of fine scale satellite cloud composites.

3. Data

The CHANCES database is a 1-yr (Feb. 1, 1994- Jan. 31, 1995) global satellite imagery database with 1 -hr temporal and 5-km spatial resolution (Vender Haar et al. 1995). Each chances image is a "seamless" global image created from a combination of geostationary and polar orbiting satellites. For this study we focused on a sector centered over the former Yugoslavia. The sector spans from approximately 23oE to 33oE and 42oN to 47oN. This falls entirely in the domain of the METEOSAT geostationary satellite.

To produce CHANCES, STC-METSAT in Fort Collins, Colorado did an enormous amount of pre-processing. This pre-processing included navigation and alignment, correction for various characteristic satellite errors, the creation of radiance background information, and the construction of binary CNC images. Kidder and Vonder Haar (1995) discuss other possible sources of error that can impact the analysis of meteorological satellite imagery including: attenuation, background contrast, contamination, displacement, foreshortening, sensor lag, signal interference, sun-satellite geometry, and viewing angle.

4. Method

Construction of composites begins with the geographic alignment of each image with a base image. This was done as part of CHANCES pre-processing as described in the previous section. In this study, we used only quality-controlled images without noise or data drops.

The aligned images were used to construct seasonal cloud frequency of occurrence composites for each hour of the day for the Yugoslavia/Adriatic sector. Figures 1 a -1 d are cloud frequency of occurrence composites for 12, 15, 18 and21 UTC, respectively. For this study, the summer season data spans the forty-five day period from June 22, 1994 to August 5, 1994.

In figures 1a -1 d, the frequency at each pixel was computed by simply dividing the number of cloudy days at each hour at that pixel by the number of days with cloud data available at that same pixel. The resultant cloud frequency of occurrence at each pixel was then assigned a specific brightness and displayed as a composite image. Variation of brightness from pixel to pixel in an image represents the variation in cloud frequency from location to location. The actual percentage frequency value can be estimated by comparing the brightness of the target pixel with the scale at the bottom of each image. The scale spans from O percent on the left (black) to 100 percent on the right (white).

Conditional probability images were prepared by comparing each image from an initial time with an image from a forecast time. If a cloud (or no cloud) exists at a pixel on the initial image and a cloud exists at the same pixel location of the target (forecast) image it is summed for that pixel. An algorithm repeated this process for every pixel of every image for each of the forty-five days of summer 1994 to compile data for one to twelve hours beyond each hour of the day.

Six hours represents the most important forecast interval for Air Force terminal aerodrome forecasts (TAFs) since active TAFs are updated every six hours. Target forecasts for offensive strikes, or reconnaissance missions may need accurate cloud forecasts with a six to twelve hour lead time or greater.

We compiled persistence data for two simple types of conditional probability forecasts: (1) Cloudy at forecast time given cloudy at initial time (type 1) ; (2) Cloudy at forecast time given clear at initial time (type 2) . Two other scenarios (clear at forecast time given clear at initial time and clear at forecast time given cloudy at initial time) can be constructed from (1) and (2), respectively, by subtracting the probability of being cloudy at forecast time from 100 percent. As with the cloud frequency data, the conditional probability (persistence) data can also be displayed as an image. Figures 2a and 2b are type 2 conditional probability images for six and nine hours after 6 UTC (8 LST). Figure 2a represents the probability of cloud at 12 UTC (14 LST) at each pixel when the pixel is clear at 6 UTC. Similarly, figure 2b depicts the probability of cloud at 15 UTC (17 LST). Following images through chronologically from the initial time (including the intermediate times not shown), one finds that the quality of a persistence forecast of clear for this sector goes down with time (e.g., the probability of cloud goes up). This is a signal of the convective diurnal cycle of cloud cover over this region in summer.

With cloud frequency and cloud persistence data, you have all the necessary tools to produce simple probability forecasts for cloud at each pixel. Reinke et al. (1990) suggest various techniques. They note that a cloud frequency composite itself can be used as a forecast tool. The frequency of occurrence of cloud over each pixel at any given time is a reasonable first guess for a cloud/no cloud forecast at that location. Individual composites can be compared to note the change in frequency of occurrence of cloud at a location. This would represent the systematic variation of cloud cover over that pixel. To account for random variation in cloud cover you need to consider information in the persistence images. Reinke et al. (1990) suggest two ways to include the persistence data. First, you could compute cloud occurrence probability by adding the cloud persistence probability to the frequency. Second, you could use both probabilities in a forecast matrix in which the final probability is based on the cloud frequency and/or conditional probability exceeding a pre-determined threshold. To get even more sophisticated, the initial image could be stratified by wind direction, air mass, or other climatologically significant variable as has been done by the Air Force Combat Climatology Center (AFCCC, formerly ETAC) for many years with conditional climatology ceiling and visibility tables.

For this study, we develop a forecast tool for Sarajevo that combines cloud frequency and persistence data (Tables 1 and 2). These tables were created by extracting cloud frequency and persistence information from many composite images for the pixel centered directed over Sarajevo. As a forecaster, this type of data would be a valuable asset for a TAF or target forecast. From personal experience, we believe that the greatest inhibitor to an accurate target forecast is not having first-hand knowledge of the weather in the target area. For remote targets, satellite-derived conditional probabilities (Tables 1- 4) could be a viable surrogate to first-hand experience and substitute for the conditional ceiling and visibility tables familiar to forecasters in any Air Force base weather station. A forecaster could combine these statistics with knowledge of the current and forecast synoptic and mesoscale weather conditions to optimize the forecast. In the results section below, we discuss an empirical climatological forecast index developed in this study.

In Tables 3 and 4, we present a more sophisticated type of conditional probability computed for Sarajevo. For these statistics the initial condition was stratified by the percentage of cloudy or clear pixels in a 15 km x 15 km region surrounding the target location. The initial conditions were divided into three categories: (1) Less than 33 percent of pixels cloudy (clear) at initial time (Table 3); (2) 33 to 66 percent of pixels cloudy (clear) at initial time (not shown); (3) 66 to

100 percent of pixels cloudy at initial time (not shown). Table 3 depicts the conditional probability of cloud over Sarajevo at forecast times of 1-12 hours given the 33 percent or less of the pixels within 15 km of the target are overcast at the initial time. This adds a level of spatial dependence to the conditional probabilities that cannot be well duplicated with surface observation data, especially as the radius from the target increases. For instance you could expand out to 25 km from the target pixel. In the next section we compare these spatially conditional probabilities to the single pixel conditional probabilities presented in Table 1.

5. Results/Discussion

Figure 3 is a histogram of the average cloudy infrared pixel counts at each hour of the day for the Yugoslavia sector shown in figures 1 and 2. This represents the systematic change in cloud cover for the summer season. The minimum occurs just after sunrise at 7 LST (5 UTC) while the maximum occurs at 18 LST (16 UTC). This suggests that a majority of the summer season cloud cover is convective in nature. Figure 4 is a histogram of IR pixel counts at each hour of the day with a brightness temperature less than -40°C to isolate deep convection. The maximum occurs at 17 LST (15 UTC). The second column of Table 1 contains the cloud percentage frequency of occurrence at each time of day for the pixel centered over Sarajevo. Just as with the seasonal average for the entire sector (Fig. 3), there is a maximum in cloud cover at 18 LST (16 UTC). The data from Table 1 represents the systematic variation of cloud over Sarajevo, and would make a good climatological forecast in the absence of other data. However, the forecast could be greatly improved by combining the frequency statistics with cloud persistence data. Table 2 is a YES/NO climatological cloud forecast decision matrix constructed by combining the frequency and persistence data (Table 1) into a single binary index. " 1" (YES) is a forecast for cloud and "O" (NO) is a forecast for clear.

Although definitive YES/NO cloud criteria are certainly a topic for further research, we use the following criteria for this study. Of the two types of data in Table 1 (frequency occurrence and conditional probability), the conditional probability is a more reliable forecast tool since it includes an initial condition. Therefore, we weight the YES/NO cloud decision more heavily to the persistence probability. If the conditional probability at any hour is greater than 70 percent, then the forecast for cloud is YES. If the persistence probability is less than 70 percent, but greater than 50 percent then we compute the average of the frequency of occurrence and the persistence probability for the forecast time. If the average is greater than 60 percent then the forecast is YES ("l"), otherwise it is NO ("O"). These particular thresholds were chosen so that the mean amount of cloud predicted in the YES/NO matrix of Table 2 was comparable to the average frequency of occurrence of cloud for all hours from column two of Table 1. The average of the frequency of occurrence for all the hours is 41 percent. Assigning 1 for YES and O for No, the average frequency of occurrence of cloud as predicted by the corresponding forecast matrix (Table 5) is 44 percent.

The importance of this weighting scheme is illustrated in Table 1. At 4 UTC (6 LST) the systematic frequency of occurrence of cloud is 17 percent. However, when cloud occurs at 3 UTC the probability of cloud at 4 UTC is 83 percent. Similarly, the conditional probability of cloud at 6 UTC given cloud at 3 UTC is 67 percent compared to a systematic occurrence of 14 percent. This meteorologically makes sense for Sarajevo. In the early morning any cloud is probably not convective but rather is part of a synoptic scale disturbance and hence would be more likely to persist due to larger scale dynamics. Other data in Table 1 further illustrate the importance of heavil y weighting the conditional probability in the forecast index. Note that given cloud over Sarajevo at 6 UTC, the 12 hour forecast for cloud at 18 UTC is 100 percent. The systematic variation of cloud for summer 1994 was for overcast 68 percent of the time at 18

UTC. In fact, given an initial condition of cloud at any hour after 5 UTC, the conditional probability of being overcast at 18 UTC is higher than 68 percent.

As mentioned in the previous section of this paper, a more sophisticated approach is to stratify the probability in terms of a percentage of pixels in a region surrounding the target that are cloudy (clear) at the initial time. Table 4 is a forecast matrix derived from the persistence probabilities and cloud frequencies in Table 3. By considering pixels in a 15 km region surrounding the target in the conditional probability, as opposed to a single pixel, the forecast can change significantly. Table 4 is a CNC forecast matrix analogous to Table 2 with an initial condition of less than 33 percent of pixels within 15 km of the Sarajevo pixels classified as overcast. Comparing Table 4 to Table 2, one can qualitatively see that the amount of YES ("1") cloud forecasts is greatly reduced. The mean cloud forecast for all times in Table 4 is 21 percent. In contrast, the mean cloud amount from Table 2 is 44 percent. The mean amount of cloud predicted with an initial condition of 66 percent of pixels within 15 km cloudy is 44 percent. Evidently, considering only a single pixel at the initial time is equivalent to assuming overcast conditions over a larger region. This same bias would likely occur with conditional probabilities computed using cloud cover statistics from the conventional surface observations of a single station.

6. Conclusion

In this paper we have described forecasting applications of high resolution satellite cloud climatologies and developed a climatological forecasting tool that is well suited to the operational environment. The feasibility of creating a global database of IR data at full resolution was demonstrated by the CHANCES project (Vender Haar et al. 1995). To make the tool complete, the database should be expanded to at least five years and tables created for every pixel for each month of the year for the entire globe. The climatological forecast tool described in this paper would lend itself perfectly to software that would allow a user to point and click at the desired location on a map and instantly display the climatological data through hypertext links, like those used on web pages.

In this study we demonstrated the importance of including the spatial pattern of cloud surrounding the target in creating conditional probabilities. A second level of sophistication would be to include a temporal pattern of cloud. For instance, the initial condition could be comprised of three or six hours of cloud data at the target pixel or in an area surrounding the target.

Currently, researchers at the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University are developing techniques to extract layered cloud information from the CHANCES database. A paper on their results was presented at the 1996 Battlespace Atmospherics Conference (Forsythe et al. 1996). The location of the bases and heights of clouds are of great importance in a target forecast. Stratifying the data in terms of meteorological variables such as wind direction and air mass would make the climatology even more reliable. The level of sophistication is virtually limitless.

The potential military and civilian forecasting applications of very high resolution satellite cloud climatologies are exciting. Combat weather forecasters could use this technique in the field to greatly improve cloud forecasts. With a single observation, the weather warrior could quickly access climatological forecast aids such as the forecast matrix developed in this study using their tactical lap top computer. With the global coverage of meteorological satellites, high resolution climatological cloud forecast tools for airfields and remote targets anywhere in the world are within our grasp.

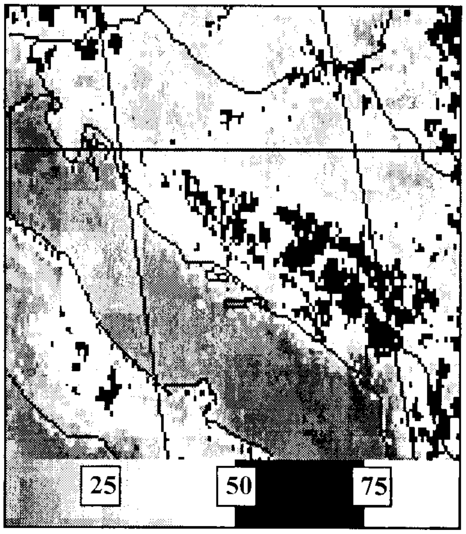


FIG. la. Cloud frequency composite from METEOSAT satellite for June 22, 1994 to August 5, 1994 for 12 UTC.

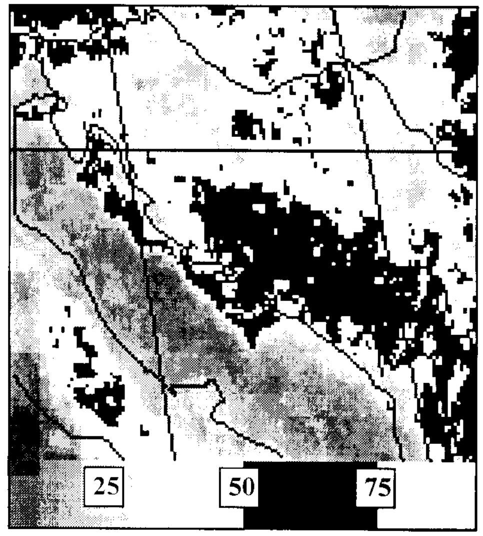


FIG. 1 b. Cloud frequency composite from METEOSAT satellite for June 22, 1994 to August 5, 1994 for 15 UTC.

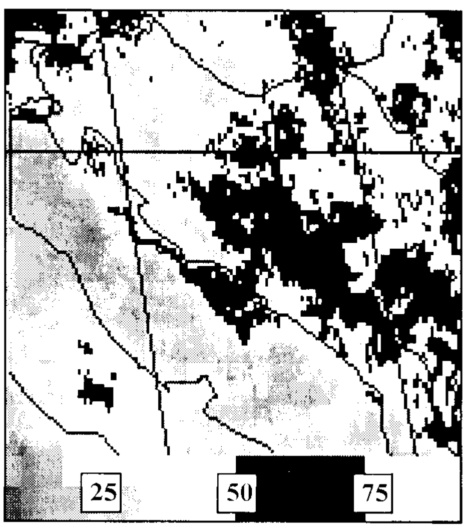


FIG. lc. Cloud frequency composite from METEOSAT satellite for June 22, 1994 to August 5, 1994 for 18 UTC.

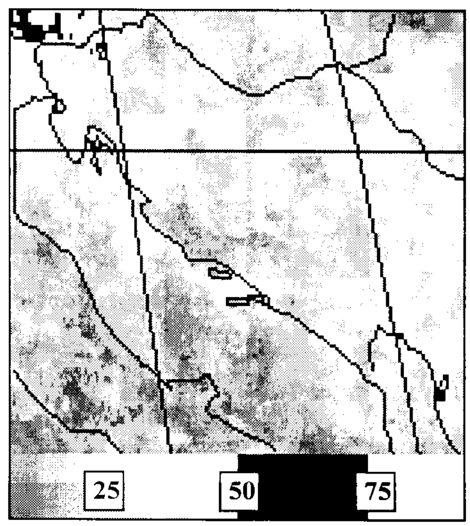


FIG. Id. Cloud frequency composite from METEOSAT satellite for June 22, 1994 to August 5, 1994 for 18 UTC.

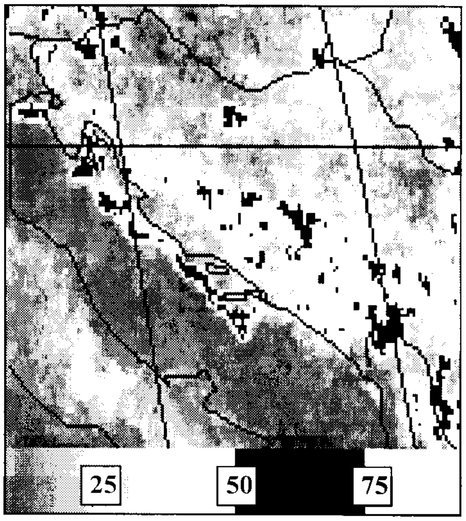


FIG. 2a. Probability **of cloudy or clear** persisting at 12 UTC from initial value at 6 UTC June 22, 1994- August 5, 1994.

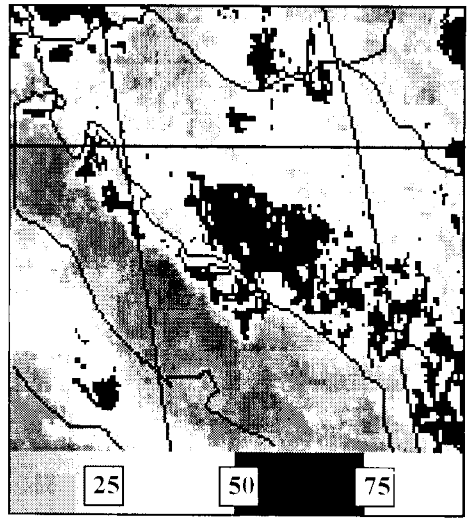
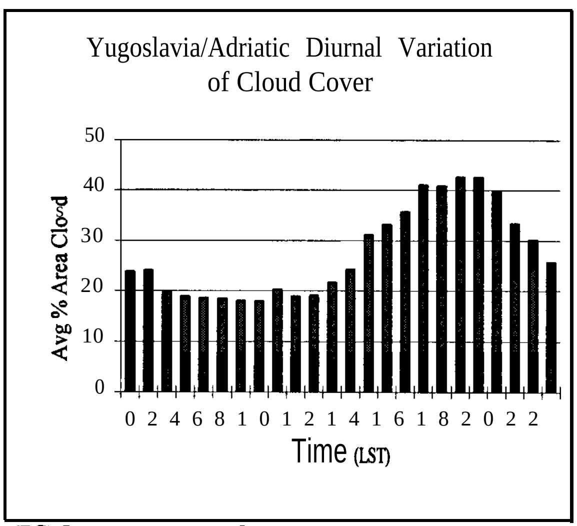
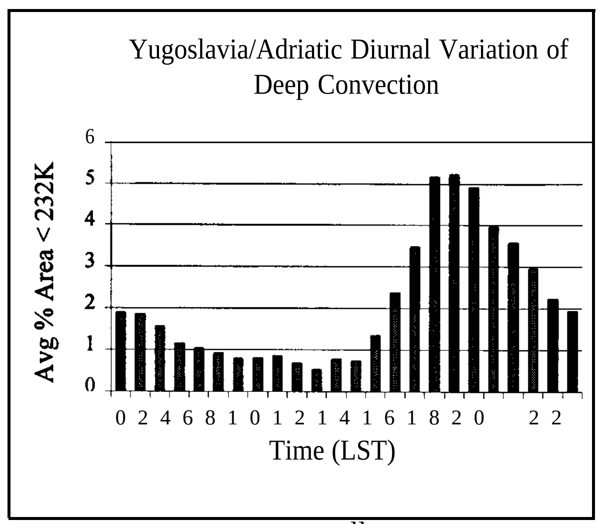


FIG. 2b. Probability of cloudy or clear persisting at 15 UTC from initial value a 6 UTC June 22, 1994- August 5, 1994.



'IG. 3: Histogram of average daily percentage of area covered by cloud June 22,1994- August 5, 1994 at each time of day.



IG. 4. Histogram of average sally percentage or area covered by cloud colder than 232 K June 22, 1994- August 5, 1994 at each time of day.

TABLE 1. Conditional probabilities of cloud at all times given cloud at initial time for Sarajevo June 22, 1994- August 5, 1994. Forecast hours are labeled 1 to 12 in the first row.

Time (UTC)	Cld% Freq	1	2	3	4	5	6	7	8	9	10	11	12
0	24	71	75	50	63	43	38	43	50	57	63	75	75
1	21	75	63	50	43	50	50	57	71	63	75	75	88
2	19	75	63	43	50	43	38	50	50	63	63	88	71
3	14	83	60	67	50	50	75	67	83	83	100	83	83
4	17	83	71	57	57	80	71	100	100	100	100	100	100
5	18	67	67	60	57	67	71	71	100	86	88	71	86
6	14	67	67	80	67	100	100	100	100	100	100	100	100
7	46	71	83	86	100	100	83	83	100	100	86	100	71
8	26	71	86	100	100	67	67	100	100	86	100	71	71
9	40	67	80	80	80	70	89	90	70	90	67	40	78
10	46	92	92	77	69	92	93	79	86	77	57	67	50
11	65	94	94	89	100	100	89	94	67	44	50	33	29
12	68	87	83	86	87	83	91	64	43	45	32	30	24
13	71	88	84	81	77	79	56	35	46	28	28	30	27
14	58	92	88	79	82	55	38	36	22	26	22	19	13
15	72	97	83	81	59	43	44	28	30	26	24	21	14
16	76	81	80	55	39	41	29	28	26	23	21	14	17
17	64	92	67	46	48	35	31	30	26	25	17	17	16
18	68	67	50	52	36	31	29	26	25	17	21	20	20
19	46	65	78	53	47	43	43	40	27	27	29	19	15
20	33	77	46	46	36	33	33	17	25	29	15	20	9
21	37	64	57	50	50	50	33	33	36	23	18	27	36
22	22	78	63	75	75	50	38	38	38	29	43	44	43
23	20	57	83	67	50	50	43	43	33	60	57	50	80

TABLE2. Cloud forecast matrix based on cloud frequency and conditional probability data in Table 1. If conditional probability >70% value is "1." If conditional probability is <70% and>50%, then value is " 1" if average of conditional probability and cloud frequency for forecast time is >60%. "1" is a forecast for cloud, and "0" lea rear.

Time (UTC)	1	2	3	4	5	6	7	8	9	10	11	12
0	1	1	0	0	0	0	0	0	0	0	1	1
1	1	0	0	0	0	0	0	1	0	1	1	1
2	1	0	0	0	0	0	0	0	1	1	1	1
3	1	0	0	0	0	1	1	1	1	1	1	1
4	1	1	0	0	1	1	1	1	1	1	1	1
5	0	0	0	0	0	1	1	1	1	1	1	1
6	0	0	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1	1
9	0	1	1	1	1	1	1	1	1	0	0	1
10	1	1	1	1	1	1	1	1	1	0	0	0
11	1	1	1	1	1	1	1	0	0	0	0	0
12	1	1	1	1	1	1	1	0	0	0	0	0
13	1	1	1	1	1	0	0	0	0	0	0	0
14	1	1	1	1	0	0	0	0	0	0	0	0
15	1	1	1	0	0	0	0	0	0	0	0	0
16	1	1	0	1	0	0	0	0	0	0	0	0
17	1	0	0	0	0	0	0	0	0	0	0	0
18	1	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	1	0	0	0	0	0	0	0	0	0	0	0
21	1	0	0	0	0	0	0	0	0	0	0	0
22	1	0	1	1	0	0	0	0	0	0	0	0
23	0	1	0	0	0	0	0	0	0	0	0	1

TABLE 3. Conditional probability of cloud given 1 -33% of pixels within 15 km of Sarajevo covered with cloud at initial time June 22, 1994- August 5, 1994.

Time (UTC)	Cld% Freq	1	2	3	4	5	6	7	8	9	10	11	12
0	24	33	0	0	0	0	0	0	33	33	33	67	67
1	21	0	0	0	0	0	0	0	0	0	0	0	0
2	19	0	0	0	0	33	33	33	100	67	100	33	33
3	14	40	40	20	60	40	60	60	80	80	60	60	80
4	17	50	50	50	0	0	0	0	0	50	50	50	50
5	18	33	33	0	0	33	33	33	67	100	100	67	100
6	14	25	25	25	25	50	50	75	75	75	75	75	75
7	46	0	0	25	25	25	75	75	75	75	50	50	25
8	26	50	75	75	75	100	100	100	75	100	100	50	50
9	40	33	67	67	83	83	83	67	83	83	50	33	17
10	46	83	83	83	83	83	83	83	83	67	33	33	17
11	65	38	50	25	38	38	25	25	13	13	13	0	0
12	68	64	55	55	45	27	27	9	0	18	9	9	18
13	71	40	80	60	60	40	20	20	20	20	20	0	0
14	58	50	50	33	50	50	33	50	33	17	17	17	17
15	72	0	0	0	0	0	0	0	0	0	0	0	0
16	76	14	43	43	14	29	14	0	14	14	14	14	14
17	64	50	33	17	17	0	0	0	0	0	0	17	17
18	68	0	0	20	0	0	20	20	20	20	20	20	0
19	46	13	13	0	0	13	13	13	13	13	0	0	0
20	33	20	0	0	0	0	0	0	0	0	0	0	0
21	37	0	0	0	0	0	0	0	0	0	0	0	0
22	22	0	33	0	0	0	33	33	0	0	0	0	67
23	20	50	25	50	25	0	0	0	0	0	25	25	25

TABLE4. Forecastmatrix as in Table 2except with initial condition of l-33% of pixels within 15 km of Sarajevo classified as cloudy.

Time (UTC)	1	2	3	4	5	6	7	8	9	10	11	12
0	0	0	0	0	0	0	0	0	0	0	1	1
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	1	1	1	0	0
3	0	0	0	0	0	1	0	1	1	1	1	1
4	0	0	0	0	0	0	0	0	1	0	1	1
5	0	0	0	0	0	0	0	1	1	1	1	1
6	0	0	0	0	0	0	1	1	1	1	1	1
7	0	0	0	0	0	1	1	1	1	0	0	0
8	0	1	1	1	1	1	1	1	1	1	0	0
9	0	1	1	1	1	1	1	1	1	0	0	0
10	1	1	1	1	1	1	1	1	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
12	1	0	0	0	0	0	0	0	0	0	0	0
13	0	1	1	1	0	0	0	0	0	0	0	0
14	1	1	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0

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